io. 1 Considerations for lunar base at las.

### Lunar Base

Speculation with regard to a permanent lunar base has been with us since Robert Goddard was working on the first liquid-fuelled rockets in the 1920's. With the infusion of data from the Apollo Moon flights, a onoa speculative area of space exploration has become an exciting possibility. A Moon base is not only a very real possibility, but is probably a critical element in the continuation of our piloted space programme. This article, originally drafted by World Space Foundation volunteers in conjunction with various academic end research groups, examines some of the strategies involved in selecting an appropriate site for such a lunar base. Site selection involves a number of complex variables, including raw materials for possible rocket propellant generation, hot and cold cycles, view of the sky (for astronomical considerations, among others), geological makeup of the region, and

nore. This article summerizes the key bese siting considerations and suggests some alternatives. Availability of pocific resources, including energy and certeinminerals, is critical to success,

#### 7 troduction

Of nineteen lunar surface sites exlored to date, a diversity of features nd characteristics have been examred, If the first lunar "resource" is Information, then the utility of a locale of the In-situ and observational scinces will rank high, Early site selecon will be governed by safety, econmy, and Immediate utility of the reources already known. Later site elections will depend on new knowldge of all types of resources (Fig. 1).

Present discussion of base sites is riven most strongly by {he scientific ommunity with consideration to engleering feasibility and eventual reource utilization. lunar geology, luar geophysics and other disciplines oncerning the Moon and its environs selenology) dominate one branch of cientific utilization, while use of the loon as a platform for astronomy, pace physics, Earth and solar obserations dominates the other branch. erlying any discussion of she selecon for those uses are the sultability I local terrain, viewing of the Sun,

BY ROBERT L. STAEHLE, JAMES D. BURKE, GERALD C. SNYDER Jet Propulsion Laboratory, California Institute of Technology

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Earth and heavens, availability of energy and heat rejection paths, and local material resources.

One of the earliest discussions of lunar base location was put forth in 1920 by Robert H. Goddard, a pioneer In American rocketry. He noted, "The best location on the Moon would be at the north or south pole with the [propellant] liquelier in a crater, from which the water of crystallization may not have evaporated, and with tho [solar) power plant on a summit constantly

ig. 2 Sinuous I tadley Rille was the landing site for Apollo 15, located near the bottom-centre edge of its photograph. North Is 10 the right, the Apendines by to the East, just off the bottom edge Atthough iero may be more optimal lunar base sites. Hadlay Rille would be a reasonable choice.

exposed to the Sun, Adequate protection should, of course, be made against meteors, by covering the essential parts of the apparatus with rock," (see p. 405, upper picture). Many would still credit him with a valid conclusion, even though geologists will offer different explanations If volatiles are found at the poles. Recent ground-based radar indications of the possibility of ice near Mercury's poles weakens some arguments against the possibility of lunar polar ice by suggesting that solar wind erosion may be less important than proposed in limit-Ing ice buildup.

Early locales with diverse materials are likely to outrank locales with the highest concentration of a single desired substance. The exception may be any site with a concentration of hydrogen or carbon in some form, such as Ices or subsurface gas reservoirs. Scarcity of these types of reducing agents has come to be the dominant limitation In most discussions of lunar resource utilization.

Geologists wanl 10 sample and record a diversity of terrain representing the major geologic phases of the Moon's formation and evolution. Mare and highland sampling at many sites Is considered essential, with age diversity Important.

Energy Is another resource, certainly for surface operations, and perhaps even for export, If nuclear powor Is unavailable at the required levels, energy storage equipment for the 14day night Is Important, High crater rims and peaks near both poles may offer near-constant solar Illumination, and modest towers at these locations certainly will, but a thorough lighting survey has yet to be conducted to pln down the best locations.

Any location on the Moon would do for a partial gravity test facility for life

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knowledge the prior work of many others referenced hit the original publica-tion, adapted here with permission of the World Space Foundation

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#### ■ TO THE MOON ■

# Siting

sciences investigations. For photosensitive organisms, polar locations could offer piped-in sunlight on any day-night cycle researcher might choose.

Flight mechanics into and out of a base site can be an Important consideration. Equatorial and polar sites are favoured for their near-constant accessibility.

Slopes and terrain features can bo resources themselves. Slopes offer lavoured illumination and shadowing, while craters offer natural depressions for astronomical instruments, barriers to lander exhaust-driven debris, reactor shields and other uses. Elevation differences also figure into some energy storage schemes.

Surface mobility will influence sl10 selection by dictating the range d accessibility from a core base site. Subsidlary sites can serve a variety 01 specialized purposes, such as mining where different ores are accessible. Sensitive astronomical instruments will nood to be away from frequent surface activities. After accounting for the diffraction of the signals of these activities, we find that if a main base is located near the limb as viewed from Earth (i.e., 90 degrees longitude), a subsidiary site at about 101 degrees east or west longitude affords sufficient radio Isolation from Earth at the limits of the Moon's east-west libration (or "wobble").

If we had to choose a site today and be certain of a workable, if not at all optimal locale, the Apollo 15 landing site at Hadley Rille (fig. 2) would be a reasonable choice. But we can afready see superior sites, though we do not know precisely where it is safe to put the base's first landers down. Virtually all investigators agree on the wisdom of a lunar polar orbiter with suitable composition-measuring instruments plus Imaging, Surface rovers may be advisable at "finalist" sites, while teleoperated (remotely controlled) rovers will surely play an important role in exploration from any base site, Early missions could even be used to build a cache of some useful product, such as oxygen, for use by later human explor-

As important as further lunar reconnalssance is, terrestrial development and testing of alternative resource extraction processes Is essential. Operation of one or more lunar baso analogs (as in ground-based simulations) would offer invaluable experience at a fraction of the cost of making mistakes on the Moon. Determination of the most workable and economical resource extraction processes will influence any resource-driven site selection.

Fig 3 Lunar outpost site near Mare Smythli

#### Base Selection Criteria

The search for potential lunar base sites is a complex undertaking. There are widely dispersed lunar sites of Interest for known and potential resources, selenology (the science of the Moon and Its environs), and observatories. Important characteristics Include certain geological and topographic features, local mineral and rock composition, solar illumination, view of Earth and tho celestlal sphere. and soil engineering properties (including usability as a construction material, etc.), Space vehicle arrival and departure trajectories favor equatorial and polar sites. Over time, base sites will be developed serving different purposes. information may be tho Initial lunar "resource," in the form of observational and on-site research. Resource-driven sites may see the fastest growth during early decades of lunar development, but selection of initial sites is likely to be driven by suitability for a combination of activi-

Only equatorial locations offer nearly all-sky views for astronomy, while most of the far side offers radio isolation. Such Isolation could offer radio astronomers a view of the Universe unfettered by television broadcasts and a host of other terrestrial Interference, A base in MareSmythil (Fig.3) with subsidiary outposts would be favorable for a variety of purposes, and would proserve a broad resource flexibility. Discovery of accessible volatiles (substances which

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are easily vaporized, such as hydrogen, water and carbon dloxide, which often turn out to be useful for sustaining life and making rocket propellants), in the form of polar permafrost, subsurface gas reservoirs, or comet impact remnants, would dramatically increase the attractiveness of such a she from a logistical support arrd selenological point of view. For example, a ready source of waterice would allow the manufacture of hydrogen and oxygen for the trip home or to of her destinations (It should be noted that no reliable evidence of such volatiles exists). With the availability of nearconstant sunlight for power generation and permanently shadowed areas at cryogenic temperatures, polar sites require substantially loss Earthlaunched mass and lower equipment complexity for an initial base. Polar sites are, however, scientifically less interesting with their limited view of the sky and absence of important types of terrain common at lower latitudes.

Reliable evidence exists for areas of certain mineral concentrations, such as ilmenite, which could form a feed-stock for some proposed resource extraction schemes, In addition to being a source for oxygen and iron, ilmenite (composed of iron, titanlum, and oxygen) harbors higher concentrations of solar wind-implanted hydrogen, carbon, nitrogen and helium. These elements were apparently exhausted from the Moon during its formation and evolution, but minor con centrations have collected out of the

#### ■ TO THE MOON ■

tenuous plasma discharged from tho Sun and driven across the Solar System as the Solar wind. New data from a lunar polar orbiter are essential for the most Informed site selection. Data from the first Galileo flyby have already revealed previously unknown features and will aid surface mineralogical characterization.

#### The Present Understanding of the Moon

The last unmapped region of the Moon, near the south pole, was photographed during the December 8, 1990 Galileo flyby, but there Is a great deal more that would be helpful to know In selecting base sites, From Ranger through Apollo the trend has been to open up mission constraints to afford better scientific opportunities. Apollo 11 was sent to a flat mare region for safety. In contrast, the Apollo 17 site was selected for Its geological diversity within a small area (Fig.4).

I-he last three Apollos carried a set of orbital Instruments designed to map the surface et fine resolution and infer Its composition, but near-equatorlal orbits limited their coverage to less than 20% of the Moon. Crude geologic maps of the entire surface havo been constructed from the best available data of all types.

Information needed for selecting the best base sites depends on the objectives of these bases. However, some kinds of data are required for nearly any base. local topography is an obvious need, and most investigators agree that, except for the Immediate vicinity of the Apollo sites, present Information is inadequate. Even without elevation data, positions of features are typically uncertain by 1-3 km on the near side, by 3-6 km poleward of 65 degrees latitude, and by '3-15 km on the far side (It is Important to remember, though, that terrestrial explorers soldom knew their locations a fraction as accurately).

An orbiting laser altimeter and a metric camera system offer the preferred means for improving lunar topographic maps. Knowing topographic obstacles is essential for safe approach from and departure to orbit, as well as for designing solar power and thermal radiation Installations for a specific site. Spatial resolution of 1 meter or better is preferred to certify landing sites.

1 he next most important new information probably concerns the subsurface mechanical properlies, to a depth of at least a meter, that affect digging, foundation-building and other preparations al any specific site. Where mining is contemplated, such information is important to a greater depth. Though the lunar surface has been somewhat homogenized by Impacts, It does vary in state of compaction, grain

size distribution, sizo of embedded rocks and other mechanical proper-

While compositional properties may be less Important than local topography and soil mechanics during tho earnest lunar operations, composition will dominate once resource development begins. Compositional information is therefore highly desirable even before choosing the first base site.

Multispectral remote sensing from orbit provides needed regional data. after which surface traverses are best tor detailing the most promising locales, Long range rovers teleoperatod from Earth carrying Imaging, geochemical and geophysical instruments, would be sultable for both scientific and resource she reconnaissance. Use of these rovers could continue during base build-up.

Depending on a short list of candidate sites, different kinds of local Information may be useful for selecting a final site. For a polar site, an orbiter with altimetry and metric Imaging could perform a survey of varying surface lighting conditions for siting solar power generators, radiators and Instruments. In the event an orbiter detects indications of volatiles near one of the poles, surface exploration may be required for precise

Fig. 4 Arrow Indicates 1110 Apollo 17 landing site mear a location. In a similar fashion, it could variety of geologically interesting formations. prove useful to explore volcanic ar-

#### Transportation Surface

lunar Outpost is the title of a publication that depicts concepts developed during the Lunar Base Systems Studyundertaken by the Advanced Programs Office, in the Engineering Directorate of the Johnson Space CentOr, In 1988-88, it was recognised at the timo that the spacecraft concepts presented may not be the ones that will eventually fly and that some of the elements described may not even be built. Its purpose was not to present a preferrod path or "road map" to the Moon, but to enlighten tho reador on the needs of lunar exploration and development, and to challenge the reader to formulate new ideas and concepts, We present here the section on 'Surface Transportation'.

Lunar surface transportation is designed to move people and equipment to accomplish local objectives and perform long distance missions including the mapping and surveying of future mining and resource sites. Other construction tasks, such as excavation or large equipment assembly, will be accomplished by specially designed construction equipment.

The operating conditions for surface vehicles will be very different from terrestrial travel conditions. 1 he Moon has one-sixth the gravity of [ arth, practically zero atmosphere, extreme temperature swings (10? K to 384 K, or -250°F to +257°F, at the Apollo 17 site), and almost no magnetic field to provide protection from radiation. The vehicles required for lunar operation must not only survive this environment but do so over many years.

When humans return to the Moon,

the surface vehicles will be designed with the help of pasl experience Apollo missions 11, 1 ? and 141hrough 17, and the unmanned Soviet Lunokhod 1.

Two types of transportation vehicle will be required during the buildup phase of the lunar outpost: an unpressurised rover for local transportation, and a pressurised vehicle for longrange travel

The local rover, LOTRAN (local transportation vehicle, unpressurised) is designed for a range of 100 km with a maximum speed of 15 km/hlts passive suspension in the form of metal-clastic wheels simplifies the design by reducing the number of moving parts and opportunities for failure. The vehicle is fully articulated at two joints, allowing for obstacle avoidance and/or negotiation. It can carry two crewmembers plus 850 kg of

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This lunar landscape depicts the arrival of a modular chamber from Earth that could be used to form living and work quarters for personnel. The unit will be moved to the site in the background and buried for protection from meteogrammacts.

\*\*RASA artivork by Pat Rawlings\*\* This long landscape depicts the arrival of a modular chamber from Lann unit course on second unit will be moved to the site in the background and buried for protection from muleosampacts of A

eas, such as the region around Aristarchus, for possible vents and associated mineral Ization, lava tubes which could make natural base shelters and other physical and compositional features (Fig. 5).

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MOSAP and LOT RAN vehicles on a scouting mission. JSC/NASA

payload or two additional crewmentbers, depending on the task requirements. The second joint can be disconnected for trips not regulring the trailer section,

The pressurised vehicle system, MOSAP (mobile surface application traverse vehicle), has a maximum tinge of 3000 km with a nominal speed of 10 km/h, It also has a passive \$uspension in the form of cone wheels, The complete system is a four-piece modular design to allow flexibility in mission planning. Each of the four units can be individually operated or connected In the train configuration shown below and controlled by the first unit, the primary control research vehicle (PCRV). The units following the PCRV are the habitation trailer unit, the auxiliary power cart, and the experiment and sample trailer, Most tasks, such as crew transfer and medium distance survey or sample collection, will require only the PCRV.

Extremely long traverses will be accomplished by using a landing craft with crew module flying round trip from lunar orbit. Basing the landing craft at the outpost and "hopping" from site to site would not be as energy efficient.

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Flo 5 The area around the young prater Aris shore is of volcanic origin

support local operations. At least meter-deep (and preferably deeper) regolith (loose soil) is desirable for burying initial habitation structures to sullable depth for long term cosmic ray and solar flare shielding. Two meters of 100so material protecting inhabited structures from all directions, achieved by a combination of trenching and burying, is considered adequate. Mechanical properties should offer easy excavation. Ilmenite-rich mare (lunar "sea", or lowland) soll provides slightly superior radiation protection for a given thickness than lower density highland material, but this Is not likely to be decisive advantage in base construction.

Second consideration is given to reducing the need for costly importation of terrestrial malerial for functions easily replaced by lunar material. Perhaps the simplest processed lunar material is cast basalt (a family o! Igneous rocks common to the Earth and Moon, formed when certain types of lava cool on the surface. An example of basalts are the majority of the Hawaiian Islands and lunar maria). Results from Earth-based testing Indicate that basalts appear to be of sultable composition to be melted, poured Into forms, and cooled into bricks and more complex structural forms. It can also be spun Into Insulating rock wool, as has been done In some terrestrial industries for decades. Melting and sintering (heating and forming without melting) temperatures are about 200 degrees celsius less for lowland mare basalts than for typical highland materials, arrd therefore require less process heal, Materials for production ot some metals, solar cells, cement (based on CaO, calcium oxide), concrete, etc. may be more easily extracted from highlands although concentrates from mare materials will be adequate. Some highland materials produce a higher-strength, more transparent glass. For simple building materials, a mare site is superior but highland materials will work.

Volatiles In lunar samples have been shown to originate from solar wind implantation. Concentrations of hydrogen, carbon and nitrogen, the most valuable for life support and propellant, are available from lunar solls and regolith brecclas (a rock composed of chunks of smaller, older rocks which have been fused together in a geologic process). Because these elements implant over time on the surface of mineral grains, their mass concentrations are highest on smaller grains in older solls. Concentrations are much lower In solid Igneous (volcanic) rocks. Retention on Ilmenite grains Is preferential to other common minerals. It is not clear that the bulk availability of solar wind-implanted hydrogen, carbon or nitrogen is sufficlent for practical production quantities of propellant, Other possible sources of volatile compounds include cometary impacts. Water, carbon dioxide, methane, hydrogen sullide, ammonia or other votatiles are unlikely to last long near the impact points, but could collect In polar cold traps.

Simple heating of lunar soils to 700 degrees C will liberate most of the volatiles, with heating above 1050 degrees C required to obtain most of the rest. Splar-driven processes could yleld sufficient gases to make up for habitat leakage and other losses. Young crater rims and ejectablankets are probably deficient in Implanted volatiles; other areas with sufficient regolith depth (probably most of the Moon) are likely to be satisfactory, though there may be a preference for Ilmonite-enriched regions.

Specialized ore bodies could take several forms. First, "ore" should be defined as a natural concentration of a useful substance 10 a level and In a form which makes its extraction economical. Most mineral concentrations remain to be discovered. Even on Earth, ore bodies are seldom discovered and never confirmed without onsite sampling. At this point we can only suggest a few kinds of lunar materials which might prove important to base location. A preliminary list could read, in descending order of Importance: mare basalt regolith, ilmenite, iron, pyroclastic glasses with semi-volatiles, high aiuminum content highland material, and KREEP (Potassium Rare-Earth Elements, Phosphorus),

Ilmenite has been discussed as a feedstock for oxygen production by chemical reduction, for its higher soiar wind volatiles content, and for the potential to beneficiate (a preparation for processing where the useful content of the Ilmenite is enriched) it from soll using relatively simple electrostatic techniques. Howover, no one has yet demonstrated that naturally occurring lunar ilmenite can be adoquately separated from accompanying substances to form a suitable costeffective feedstock. Therefore, ilmenite availability as a major siting criterion could be a trap. Early use of Ilmenite is less often described In terms of a source of iron or titanium. Ilmenite is especially abundant (up to 20% by volume) in some Apollo 11 and Apollo t7 mare basalts. Ilmenite is most often associated with high- titanium basalts in maria. Metallic iron and rrlckel-iron grains make up a small fraction of soil, apparently tho product of meteoroid impacts, lava crystallization and a chemically reducing environment. While not considered an important early base siting criterion, availability of reduced metals such as Iron could become important later. Older terrains, with deeper regolith, presumably have more metallics, i.e., iron and nickel, which may be easily beneficiated magnetically,

For oxygen extraction, magnia electrolysis (passing an electric current through molten rock), high temperature pyrolysis (alterationthrough heat) and fluoride processing are somewhat site-independent, though process energies may vary. Ilmenite reduction and pyroclastic glass processing require site-variable feed. stocks (pyroclastic glasses are typically tiny broken beads, formed in explosive meteoroid impacts or volcanic events. They form when bits of molten rock cool too rapidly to form crystalline grains).

A conclusion of the April, 1990 Johnson Space Centerluna base workshop participants bears repeat-Ing: "... .We conclude that from the point of view of resource utilization, a viable strategy would bo to select a high titanium mare site, perhaps on or near a pyroclastic area, and near a highland area so that calcium-rich feedstock would also be available,.

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#### Introduction

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# Siting

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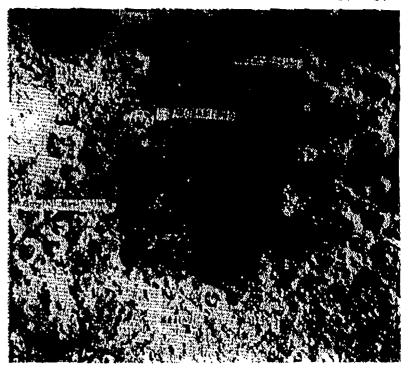


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arch (Fig.4).
The last times Apollus carried a set of orbital instruments designed 10 misp the surface at fine resolution and into its composition, but near equator ist orbits limited their coverage to less the maps of the Moon. Crude geologic maps of the entire surface have been constructed from the best available data of all types.

Information needed for selecting the best buse sites depends on the objectives of these bases. However, some kinds of dain are required for meanly any base, Local topography. Is anobylous need, canal most investigators agree that, except for the immediate vicinity of the Apollo sites, present information is inadequate. Even without cleve tion data, positions of features are typically uncertain by 1-3 km on the near side, by \$-8 km poleward of 65 degrees latitude, and by \$-15 km on the far side (it is important to remember, though, that terrestrial exploited as accurately).

An orbiting tweet altimeter and a metric camer a system offer the pretened means for improving lunar topo graphic maps. Knowing topographic obstacles is essential for safe approach from and departure to orbit, as well as for designing solar power and thermal radiation installations for a specific site. Spatial rospilition of 1 meter or butter is preferred to certify landing sites.

I he next most important new intermation probably concerns the subsurface mechanical properties, to a depth of at least a moter, that affect digging tournation solliding and other preparations at any specific site. Where it intry is contemplated, such information is important to a greater depth. Though the lunar nurface has hear somewhat nonloger 11/mil by impacts, if does very in state in compaction, grain



Fig. 4 Arrow Indicators the Applic 17 landing after cities a variety of geologically interesting formations.

size distribution, size of embedded rocks such entry conclusions properties

While compositional properties may be less important than local topography and soil mechanics during the usiliest timal operations, composition will dominate once resource development begins. Compositional information is therefore highly desirable even before choosing the first base site.

Multispectral rumote sensing from orbit provides needed regional data, after which surface traverses are best for dotalling the most promising locales, tiong range tovers teleoperated from terth onlying imaging, geochemical and geophysical instruments, would be suitable for both sometific and receipes side meetings, sance. The or these povers could continue during travelabilities.

Depending on a short list of candidate sites, different kinds of local information may be useful for selecting a final site. For a polar site, an orbitor with altimotry and metro imaging could profoun a survey of varying surface lighting conditions for aning solar power generators, radiator, and instruments, in the event an orbitor detects indications of voluntesing one of the polos, surface exploration may be required for precise location. In a similar fashion, it could prove usoful to explore volcanic ar-

### Surface Transportation

I man Outpool is the title of a publication that depicts concepts developed during the Lunar Bash Systems Study undertaken by the Advanced Programs Office, in the Engineering Directorate of the Johnson Space Center, In 1986-86. It was recognised at the time that the epococraft concepts presented may not be he that will eventually fix and time some of the elements described may not even be built. Its purpose was not to present a preferred path or "road map" to the Moon, but to enlighten the reader on the neede of lunar explomition and development, and to challenge the reader to formulate new ideas and concepts. We present here the section on "Surface Transportation".

Lunar surface transportation is designed to move people and equipment to accomplish local objectives and per form long distance missions including the mapping and surveying of future mining time resource sites. Other construction tasks, such as excavation of large equipment assembly, will be accomplished by specially designed construction equipment,

The operating conditions for surface vehicles will be very different from torrestrial travet a northform. The Moon has one-sixth the gravity of Lorth practically zero atmosphere, extreme temporature swinge (102 K to 304 K, or -250°F to (250°F), at the Apollo (7° site), and almost no magnetic flett to provide protection from radiation. The vehicles required to luntar operation must not only euroive this anvironment but do no over many years.

When humans return to the Moon,

the curlace vehicles will be designed with this help of past experience - Apollo missions 11-12 and 14 through 22 and the encounted Soviet Linok-tent.

Two types of transportation vehicle will be required during the buildup phase of the tunar outpost; an unpresended rever for local transportation, and a pressurised vehicle for long-range travel.

The local rovor, LOTRAN (local transportation vehicle, unpressurted) is designed for a range of 100 km with a maximum speed of 12 km/m. It reasons a supermitted that the transport is supermitted to the transport of the transport of the vehicle is fully articulated in two Joints, following for obstocle avoidance and/or nogotiation. It can carry two movimement plue 850 kg of

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this kinds benegated depends the universal of a medicial chambes from Parth right could be made to test better over work common, or manifold the unit safe be moved to the safe in the background and buried for intention fore memory made to the safe of contract of the translater.

eas, such as the rogion around Aristarchus, for possible vents arkl iissocloted mineralization lave tubes which could make natural base shelturs and other physical and compositional teatures (Flu. 5).

### | Material Renources

Tirst consideration of material re-I sources is given to it site's ability to

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payload or two additional crewmomhers, depending on the task requirements. The second joint can be disconnecled for trips not requiring the trailer section.

The pressurised whicle system, MOSAP (mobile surface application traverse vehicle), has a maximum range of 3000 km with a nominal speed of tu km/h. Il also has a passive cur-pension in the form of cone wheels, The complete system is a four-place modular design to allow flexibility in mission planning. Plait hi of the four units can be individually operated or connected in the train configuration shown below and controlled by the first unit the primary control research vehicle (PCHV). The units following the PCNV are the habitation trailer unit, the auxillary power cart, and the experiment and sample trailer. Most tusks, such as crow trans for and medium distance survey or sample collection, will require only, the PCHV.

Extremely long traverses will be necomplished by using a landing uself with a row module flying round, trip from lunar orbit. Hasing the landing croft of the outpost and "hopping" from \$10 to she would not be no energy efficient.

Reference during Chipest, Addition Space Contat 1988.



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z other references

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Fig. 6. The area account the young rapids Assauchus is of coloring regin

support local operations. At least meter-deep (rind preferably deeper) regolith (loose soil) is desirable for burying Initial habitation structures to suitiable depth for long term coamic ray and solar liare shielding, iw o meters of loose in aterial protecting inhabited structures from all directions, achieved by a combination of trenching and burying, is concidered adequate. Mechanical properties should offer eway excavation. Immitte-rich mare (lunor "sea", or I owland) built provides slightly superior radiation protection for a given thickness than lower density lightland material, but this is not likely to be decisive advantage in berm construction.

Second consideration is given to reducing the need for costly imports tion of terrestrial material for functions easily replaced by lunar material. Perhaps the simplest processed linar instituted to cast basalt (a family of ignoous rocks common to the Earth nart Moon, formed when certaintypes of lava cool on the surface. An example of baselfs are the majority of the Hawallan Islands and tuner maria). Hesults from Farth-based testing indidate that bacalts appear in he of sulfable composition to be melted, poured into forms, and cooled into bricks and It juic complex structural forms. If can also be spun into insulating rock wool, HIS has been done in some terrestrial industries for decades. Melting and sintering (heating and lounling without melting) temperatures are a bout 200 degrees celalus loss for lowland mare baselis than for typical highland male rials, and therefore require less process lust Materials for production of some metals, solar cells, content (bused on CaO, calcium wide), con crote, etc. may be more masily extracted from highlands although comcenti ates from more materials will be adequate. Some highland materials produce a higher- strength, more transparent glass. For simple building materials, is more alle in superior but highland materials will work.

Volatiles in Junar samples have been allown to originate from polor wind Implantation. Concentrations of hydrogen, carbon and nitrogen, the most valuable for life support and propellant, are available from lunar soils and regolith proceing tarnek composed of chunks of smaller, older rocks whileh have been fused together in digeologic process). Bectuse these elements implant over time on the sakin that, enlarg larging to ecchua concentrations are highest on smaller grains in older soils. Concentrations are much lower in solid igneous (volcanic) tocks. Reluntion on ilmenite grains is preferential to other common minorals. It is not clear that the bulk availability of solar wind-implanted hydrogen, carbon or nitrogen is sufficlinit for practical production quanti-ties of propellant. Other possible sources of volatile compounds include cometary impacts. Water, carbon dioxide, methans, hydrogen sulfide, ammonia or other volation are unlikely to last long near the Impact points, but could collect in finial cold traps.

Simple heating of luner soils to 700 degrees C will liberate most of the volatilles, with heating phove 1050 degrees C required to obtain most of the rest. Soiar driven processes could yield sufficient gases to make up for habital leakage and other tosses. Young exter rims and electa blankets are probably deficient in implanted volatiles; other areas with sufficient regolith depth (probably most Of the Woln) are likely to be suffactory, though there may be a preference to ilmonito-enriched regions.

Specialized ore budles could take several forms. First, "ore" should be defined as a natural concentration of a useful substance to a level and in a form which makes its extraction according

en acra trees, as early construction than the environd A very rop Early, as I wise the evented A very rop Early, as I wise the environd A very rop in the environment of the environment of the point Yer games by a type the Early row in point of the bordies. A state of human to be so bordies. A state of the environment of the bordies. A state of the environment of the envir

limente the beet the cussed as a facilit ack to to vigore production IP, · Bernica reo serion, loa it: . higher co larguidadille: . ottem, one — torui potential to रक्कालक है तेर के prepara pasectoropic many who he the unclot consemi-fly throughts contided it to a soir usung relatively at mpl e electro-static techniques. However, no one has you rinmonstrated that naturally unwiring tunar limenite can be ade quality separated from accompanying substances to form a suitable cost effective feedstock. Therefore, it menite availability as a major siting criterion could be a trap. I arly use a dimension is less often described in terms of a source of iron or filanium. Ilmenite is especially abundant (up to 20% by volume) in some Apollo 11 and Apollo 17 mare tyasalts. Ilmenite is. most often associated with high title nium basalis in mana. Metallic iron and nickel iron grains make up a small fraction of soit, apparently the product of rueteoroid impacts, lava crystalization and a chemically reducing environment. While not considered an important early hase siting criterion. availability of reduced metals such as iron could become important later. Older terrains, with deeper regalith, presumably have more metallics, i.e., iron and nickel, which may be easily beneficiated magnetically.

Tor oxygen extraction, magnitive tectrolysis (passing an electric current through motten rock), high temperature pyrolysis (attention through heat) and fluoridy processing are somewhat site-independent, though process energies may vary, limente reduction and pyroclastic glass processing require site-variable feedstocks (pyroclastic glasses are typically they broken beads, formed in explosive meteorald impacts or volcanic events. They form when bits of motten rock cool for rapidly to form envisabiling grants).

A conclusion of the April, 1990 Johnson Space Center lunor bace workshop participants bears repeating: ". We conclude that from the point of view of resource utilization, a viable strategy would be to select a high litanium mare allo, perhaps on or mail a pyroclastic area, and near a highland area so that calcium-rich teedstock would also be available..."

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